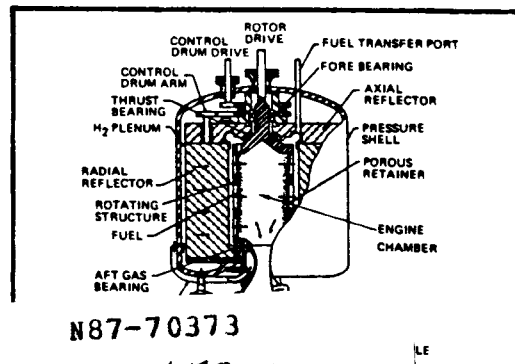
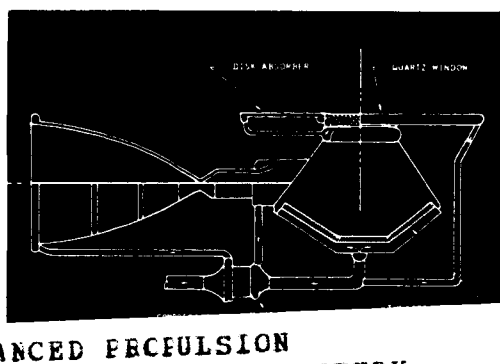
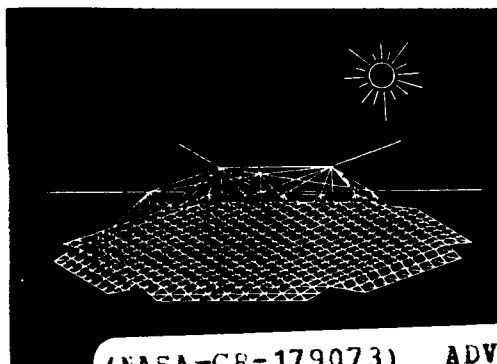
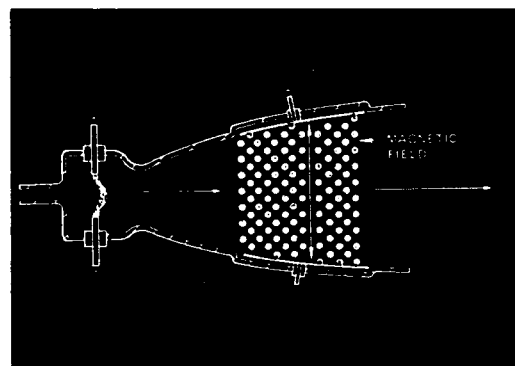
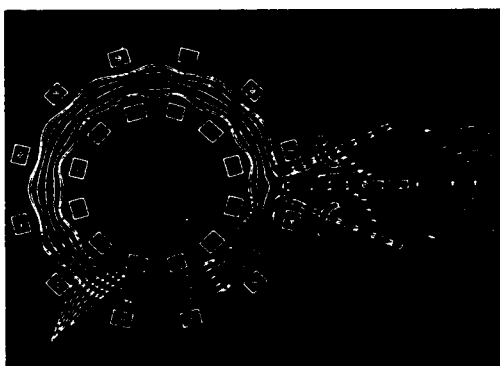
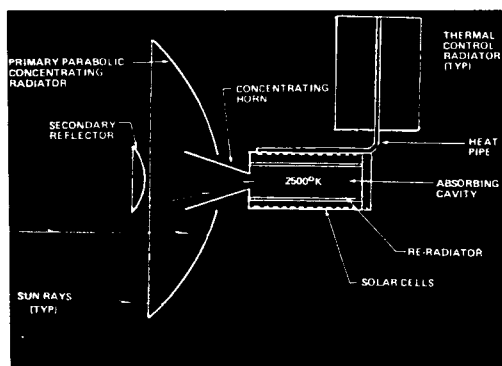
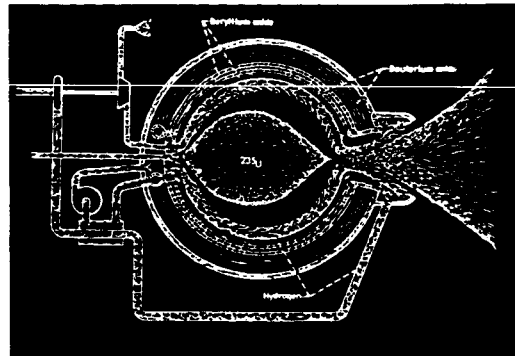
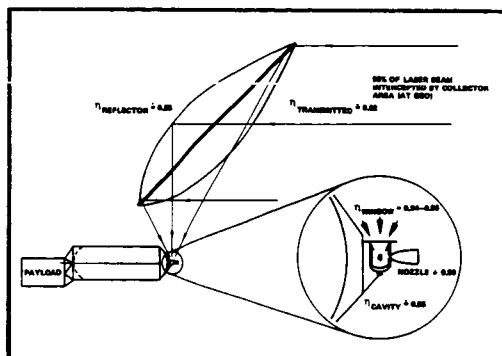


# ADVANCED PROPULSION SYSTEMS CONCEPTS FOR ORBITAL TRANSFER



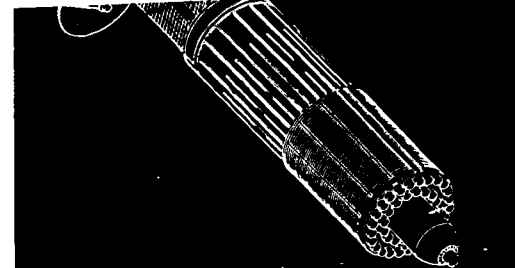
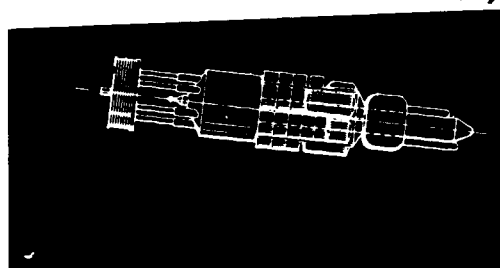
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FOREWORD

This final report of the Advanced Propulsion Systems Concepts for Orbital Transfer Study was prepared by the Upper Stages and Launch Vehicles Preliminary Design organization of the Boeing Aerospace Company (BAC) for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Contract NAS8-33935. The study was conducted under the direction of the NASA study manager, Mr. William Galloway, during the period from July 1980 through July 1981. The final report is organized according to the following three documents:

Volume I: Catalog of Advanced Propulsion Concepts  
Volume II: Study Technical Results  
Volume III: Life Cycle Cost Estimates

Key personnel during the performance of this study were:

Dr. Dana G. Andrews - Study manager, responsible for nonelectric concepts

Mr. Don Grim - Deputy study manager, responsible for electric vehicle concepts

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Constructive Criticism	V. A. Caluori

## 1.0 INTRODUCTION

The ability to transfer payloads in space is fundamentally dependent on the capability to control and apply energy. The practicality of any propulsion concept is determined by the size, mass, efficiency, and cost of the method of energy conversion from its initial form, such as high-temperature combustion gases or high-energy nuclear reactions, to the production of force or thrust. The historical dependence of aeronautical transportation progress on advancements in propulsion technology has its analog in space also. The hydrogen-oxygen rocket engine is now about 20 years old. Its latest application in the space shuttle orbiter requires that its near ultimate in theoretical potential be realized in practical application, especially with respect to efficiency and endurance. Although it is reasonable to expect this performance can be achieved, it is also evident that further progress in propulsion technology is highly desirable to more efficiently perform current visualized future missions.

This study was established to examine alternatives to the hydrogen-oxygen rocket, their availability, and their usefulness and to estimate their cost effectiveness as a replacement or partner for the chemical upper stage. The study was divided into four tasks. The first, a survey and characterization of possible advanced propulsion concepts, is covered in Volume I, Catalog of Advanced Propulsion Concepts. In the remaining tasks, the propulsion concepts found worthy of further development in Volume I were assessed as vehicles, sized for our best prediction of future mission requirements, and subjected to life cycle cost estimates over a future operations scenario. Results of these tasks are covered in Volume II, Study Technical Results. This volume contains the detailed cost estimates and methodology to generate the life cycle costs summarized in Volume II.

## 2.0 COSTING APPROACH, METHOD, AND RATIONALE

### 2.1 Approach

Costing for this study was accomplished in two phases, corresponding to the low mission model and a growth version called the high mission model. Eight vehicles corresponding to eight different mission scenarios were costed for the low model. The life cycle costs (LCC) were estimated for each scenario and then compared to determine the relative worth of each advanced propulsion concept.

Three of the eight vehicles were eliminated from the high model because of indications they would be inferior to two of the remaining concepts. LCC's for these remaining five concepts and their scenarios were then estimated for the high mission model.

### 2.2 Work Breakdown Structure

The Work Breakdown Structure (WBS) used in this study is summarized in Figure 2.2-1, displayed to level 3. It consists of three phases: DDT&E, production, and operations. Within each of these phases there are separate programs corresponding to each scenario (13 in all; 8 for the low model and 5 for the high model).

The DDT&E, production, and operations costs were estimated separately for each of the 13 scenarios (programs). Figures 2.2-2 through 2.2-4 present the full level 4 WBS. Each of the separate programs has the same level 4 WBS.

### 2.3 WBS Dictionary

Definitions for the WBS dictionary are found in Tables 2.3-1 through 2.3-4.

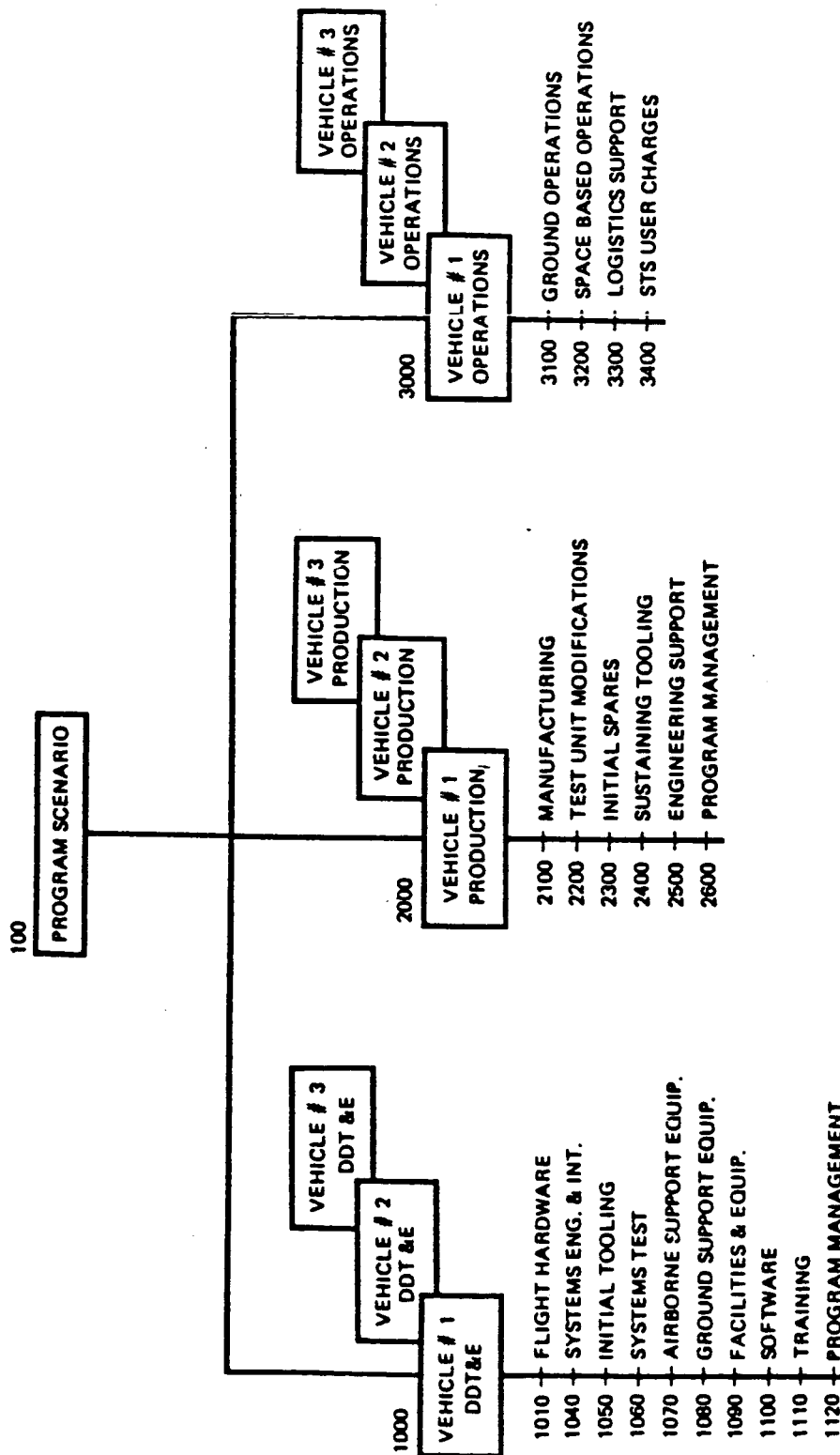


Figure 2.2-1: Advanced Propulsion Level 3 WBS

Figure 2.2-2 OTV DDT&amp;E Level 4 WBS

- 1000 DDT&E Phase
  - 1010 Flight Hardware
    - 1011 Structure
    - 1012 Thermal Control
    - 1013 Avionics
    - 1014 Power Supply & Distribution
    - 1015 Propulsion
    - 1016 Attitude Control
  - 1040 Systems Engineering & Integration
  - 1050 Initial Tooling
  - 1060 Systems Test
    - 1061 Test Hardware
    - 1062 Test Operations
  - 1070 Airborne Support Equipment
    - 1071 Structure/Mechanical
    - 1072 Fluid Systems
    - 1073 Electrical/Avionics
    - 1074 Other
  - 1080 Ground Support Equipment
  - 1090 Facilities & Equipment
  - 1100 Software
    - 1101 Flight Vehicle
    - 1102 Shuttle Interface
    - 1103 Ground Support Equipment
    - 1104 Mission Control
  - 1110 Training
    - 1111 Personnel
    - 1112 Simulators
  - 1120 Program Management

Figure 2.2-3 OTV Production Level 4 WBS

- 2000 Production Phase
  - 2100 Stage 1 Manufacturing
    - 2110 Structure
    - 2120 Thermal Control
    - 2130 Avionics
    - 2140 Electrical Power
    - 2150 Propulsion
    - 2160 Attitude Control
    - 2170 Integration, Assembly, Checkout & Test
  - 2200 Test Unit Modifications
  - 2300 Initial Spares
  - 2400 Sustaining Tooling
  - 2500 Engineering Support
  - 2600 Program Management

Figure 2.2-4 OTV Operation Level 4 WBS

- 3000 Operations Phase
  - 3100 Ground Ops
    - 3110 Pre-Launch Ops
    - 3120 Command & Control
    - 3130 Post Mission Ops
    - 3140 Maintenance/Refurbishment
    - 3150 Replacement Training
    - 3160 Engineering Support
    - 3170 Program Management
  - 3200 Space Based Ops
  - 3300 Logistics Support
    - 3310 Follow-on Spares
    - 3320 Propellants & Gases
    - 3330 ASE Spares
    - 3340 GSE Spares
  - 3400 STS User Charges
    - 3410 Basic User Charge
    - 3420 On Orbit Stay Time Charge

Table 2.3-1 Total Program Cost Definition

Cost Element Number	Cost Element Designation	Definition								
100	Total Program Cost of Each Advanced Propulsion System Scenario	<p>This element is the total cost of an advanced propulsion system scenario. It is the summation of the three major program phases:</p> <table><tr><th><u>Cost Element Number</u></th><th><u>Phase</u></th></tr><tr><td>1000</td><td>Design, Development, Testing, and Evaluation</td></tr><tr><td>2000</td><td>Production</td></tr><tr><td>3000</td><td>Operations</td></tr></table> <p>Included are all labor, material and overhead required for the design, development, fabrication, required assembly, testing and operation of each OTV. Each Phase is further subdivided into lower level cost elements which represent specific program tasks, functions, or hardware elements.</p>	<u>Cost Element Number</u>	<u>Phase</u>	1000	Design, Development, Testing, and Evaluation	2000	Production	3000	Operations
<u>Cost Element Number</u>	<u>Phase</u>									
1000	Design, Development, Testing, and Evaluation									
2000	Production									
3000	Operations									

Table 2.3-2 DDT&amp;E Phase Definitions

Cost Element Number	Cost Element Designation	Definition
1000	DDT&E Phase	<p>This cost element includes the cost to develop the Orbital Transfer Vehicle beginning with the conceptual and definition activities and concluding when the vehicle elements are ready for operational use. Included is the design, development and test of the flight hardware elements and associated ground and airborne support. Tooling, personnel training, systems engineering, facilities, software and program management are also included.</p> <p>It involves the application of scientific and engineering effort to transform an operational need into an operational system possessing the desired performance parameters. An iterative process of definition, synthesis, analysis, design, test and evaluation is utilized. Included in the effort is the integration of related technical parameters to assure compatibility of all physical, functional and program interfaces and to optimize the total system definition and design; along with the integration of reliability, maintainability, safety, human and other such factors into the total engineering effort. In addition to design and development of the airborne vehicle elements, costs include the acquisition of all ground equipment, and facilities necessary to support the vehicle development, and tooling necessary for production of test vehicles.</p>
1010	Flight Hardware	<p>This is the cost to design and develop all flight vehicle hardware, both reusable and expendable.</p>
1011	Structures	<p>This cost element refers to the cost of designing and developing the OTV Structural Subsystem. Included are all direct and indirect labor costs, material and subcontract costs and all overhead elements related to the engineering design and analysis and procurement, test and evaluation of components and subsystems in this category. Also included are procurement and evaluation of mock-ups, special test rigs, and all other supporting engineering activities.</p>

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
1012	Thermal Control	This cost element refers to the cost of designing and developing the OTV Thermal Control Subsystem. Includes all direct and indirect labor costs and overhead elements related to the engineering design, analysis, procurement, test and evaluation of components and subsystems in this category. The thermal control system consists of both active and passive means of controlling heat transfer within the OTV system. Thermal control devices or provisions which are an inherent part of a component of another subsystem are included within that subsystem and are excluded from this element.
1013	Avionics	This element refers to the design and development cost of the avionics subsystems defined below. These costs include all direct and indirect prime and subcontractor labor, materials, G&A, and fee. Costs also include component and subsystem checkout and test costs at the subcontractor level.
1014	Power Supply and Distribution	Cost to design and develop the prime energy source and the power conversion, conditioning and distribution systems. Includes all direct and indirect prime and subcontractor labor, materials, G&A and fee.
1015	Propulsion	This element refers to the cost of designing and developing the OTV and OTV drop tank main engines and engine support systems. It includes all propulsion and vehicle contractor direct and indirect labor, material and overhead costs. Integrated testing at the vehicle system level is excluded.
1016	Attitude Control	This element refers to the cost of all activities necessary to develop an attitude control system. Engines, thrusters and propellant feed system are included. Computational and sensing devices which control the orientation of attitude hardware are contained in the Avionics category.

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
1040	System Engineering and Integration	This is the cost to define the engineering requirements necessary to direct an integrated approach to design, development and operations. Includes requirements definitions, mission payload analyses, preliminary design, design integration, system optimization, interface compatibility, design reviews, technical risk assessment, technical performance assessment, countdown analysis and system engineering data.
1050	Initial Tooling	Integration activities include intersystem engineering interface tasks with contractors and government agencies. Definition of Interface Control Documents, joint operating plans and interface control plans. Also includes development of program plans and analyses for: quality control, reliability, maintainability, producibility, transportability, safety, logistics and mass properties.  Includes the cost of planning, design, fabrication, assembly, installation, and modification, maintenance and rework of all tools, including assembly tools, dies, jigs, fixtures, master forms, gauges and handling equipment for use during the manufacture of the Orbital Transfer Vehicle. Includes costs for the determination of tool requirements, planning of fabrication and assembly operations, maintaining tool records, scheduling and controlling all tooling orders, programming and preparation of tapes for numerically controlled machine parts, and preparation of templates and patterns.
1060	System Test	Refers to the cost of performing system development tests of the Orbital Transfer Vehicle. Includes test operations as well as the hardware necessary to perform the tests.
1061	Test Hardware	Refers to costs of all major units of hardware purchased or fabricated in the DDT&E Phase for all system tests or flight demonstration. Includes production cost of test vehicles and airborne support equipment hardware for the launch vehicle.

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

1062	Test Operations	Includes the costs of performing development tests using prototype hardware to acquire engineering data and confirm engineering hypotheses. The test operations include the detail planning, conduct, support, data acquisition and analysis, reports and materials consumed in ground, and flight tests.
------	-----------------	---

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
1070	Airborne Support Equipment	This element includes the cost to design and develop the equipment required to support the operation of the OTV in orbit. It summarizes tasks and services required to mate the OTV with the Shuttle, link with and separate from it. Included is the equipment for operational docking/undocking of the OTV and Shuttle, abort provisions, alignment and energy absorption, retraction/extension support, reentry purge, avionics interface, umbilical disconnects in the fluid/electrical interface, and on-orbit assembly tools and equipment.
1071	Structural and Mechanical	This element summarizes tasks, hardware and services required to design, develop and test structural and mechanical OTV/Shuttle interface equipment. This equipment consists of structural/mechanical portions of items required for OTV deployment, rendezvous and docking; interface panels; OTV/Orbiter supports, and supports for interfacing subsystems.
1072	Fluid Systems	This element summarizes tasks, hardware and services required to design, develop and test the OTV/Shuttle interface fluid subsystems. These items consist of main propellant fill, drain, dump, vent and purge provisions between the OTV and Shuttle and through the Shuttle and similar Attitude Control propellant provisions as required. Task includes qualification test of components and subsystems.
1073	Electrical/Avionics	This element summarizes tasks, hardware and services to design, develop, test, produce, install and check out the electronic and electrical equipment that provides OTV/Shuttle interfaces while the OTV is in the Orbiter payload bay and while it is entering or leaving it during a mission. Task includes qualification test of components and subsystems.
1074	Other	This element summarizes tasks, hardware and services to design, develop and test other airborne support equipment which is not yet defined but includes the hardware items and tools necessary to assemble the OTV on-orbit.

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
1080	Ground Support Equipment	Includes the cost of development engineering, testing and production of all ground-based equipment required to support the launch, recovery, and maintenance phases of the vehicles during flight test operations, flight operations or mission operations. Covered are scientific and engineering services related to research efforts, development and reliability work integral to equipment design. Costs for the testing of ground equipment consist of the conduct of the test, manufacture of mockups, test rigs, instrumentation and unique test equipment. Test equipment common to the test of ground equipment and air vehicle are considered as part of facilities costs. Production costs of ground equipment, tooling and engineering support effort and material are included here. Ground equipment is normally delivered to the launch and operations site.
1090	Facilities and Equipment	Costs for facilities include those incurred in the procurement and preparation of land; construction and/or modification of structures; installation of equipment, tools, cranes and derricks; service roads; railroad tracks; utilities, etc. Includes costs for such facilities as: vehicle and engine test; launch; operational and maintenance; manufacturing; and facility activation.
1100	Software	This element consists of the costs incurred in developing, analyzing, verifying and implementing the OTV and OTV/Shuttle interface software, both ground and airborne. It includes system and program design; program coding and debugging; program testing; and integration of programs.
1101	Flight Vehicle Software	This element consists of the cost of tasks and services required to incorporate the software for OTV onboard systems.
1102	Shuttle Interface Software	This element consists of the cost of tasks and services required to incorporate OTV generated software requirements into Shuttle subsystems or subsystems which remain with the Shuttle during the OTV portion of the missions.
1103	GSE Software	This element consists of the cost of tasks and services required to incorporate OTV related software into the ground support equipment at the manufacturing, refurbishment and launch sites.
1104	Mission Control Software	This element consists of the cost of tasks and services required to incorporate OTV related software into the ground mission and control systems.

Table 2.3-2 DDT&amp;E Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
1110	Training	Refers to the cost of instruction programs for Orbital Transfer Vehicle flight and ground crews as well as the associated simulators and equipment.
1111	Personnel Training	Refers to the cost of training both ground and flight crews to support the Orbital Transfer Vehicle Program. Excludes cost of simulators.
1112	Simulators and Equipment	Includes the design, development and manufacture of those distinctive end items of equipment designed specifically to meet training objectives such as operational and maintenance trainers, cutaways, mockups and models. Costs of facilities constructed exclusively for the training mission are included here.
1120	Program Management	Refers to the costs associated with the prime contractor's centralized effort in areas of program planning, control and administration. Includes such tasks as program documentation, financial and manpower control, interfacing with the customer and other contractors and material and project management.

Table 2.3-3 Production Phase Definitions

Cost Element Number	Cost Element Designation	Production Phase	Definition
2000		Production Phase	Refers to that portion of the OTV program where fleet vehicles and expendable hardware is fabricated. The facilities, ground equipment, airborne support equipment and tooling are acquired during DDT&E to accommodate all necessary production and operational launch rates. The costs of all reusable or expendable orbital transfer vehicles and expendable elements required to support the operational fleets are included. The costs of all necessary support and management are also included. Production costs include all direct and indirect labor, material and overhead. Contractor fee is excluded.
2100		Manufacturing	These cost elements refer to the cost of manufacturing new vehicle stages in quantities to support the operations phase of the OTV program. They include the manufacture and assembly of all hardware in the structures, thermal control, avionics, power supply and distribution, propulsion and attitude control subsystems. The integration of these subsystems into a single entity, checkout and test of the final product is also included.
2110		Structure	These cost elements refer to the cost of producing the structure system. Physical elements of the individual structural elements are the same as those defined under cost element 1011 in DDT&E phase, table 2.3-2.
2120		Thermal Control	These elements include the fabrication cost of the thermal control system. Physical elements of this system are the same as those defined in table 2.3-2 under element 1012.
2130		Avionics	These cost elements represent the cost to manufacture the avionics subsystem. Elements of the avionics subsystem are the same as previously defined in table 2.3-2 under element 1013.
2140		Power Supply and Distribution	Costs associated with the production of the power supply and distribution system. Physical elements of this system are the same as those defined in WBS category 1014 in table 2.3-2.
2150		Propulsion	These elements include the cost to fabricate the propulsion system. Physical elements of this system are the same as those defined in table 2.3-2 under cost element 1015.

Table 2.3-3 Production Phase Definitions (Continued)

2160	Attitude Control	These elements refer to the cost of fabricating the attitude control system. Physical elements of this system are the same as those defined in table 2.3-2 under cost element 1016.
2170	Integration, Assembly Checkout, and Test	Refers to the contractor activities in integrating and assembling hardware elements and subsystems into an operational system. Includes all system calibration and checkout, as well as necessary acceptance testing.
2200	R&D Vehicle Modifications	Includes the cost to inspect and appropriately modify flight test vehicles or the flight demonstration articles of the orbital transfer vehicle that are to be included in the operational fleet.
2300	Initial Spares	Includes the manufacturing cost of spare parts for the initial spares stock required for vehicle operations.
2400	Sustaining Tooling	Includes the cost of tooling maintenance, replacement, modification and rework needed in support of new vehicle manufacturing.
2500	Engineering Support	Includes the cost of engineering effort that is in direct support of manufacturing. Involves the coordination of the various manufacturing activities on an interdepartmental basis and with subcontractors and vendors. Also includes continued engineering analysis of test results and other supporting activities (product improvement).
2600	Program Management	Refers to prime contractor costs associated with providing a central direction and control of the overall orbital transfer vehicle program. Includes program planning, scheduling, budgeting, monitoring and control, documentation, coordination and other program management activities.

Table 2.3-4 Operations Phase Definitions

Cost Element Number	Cost Element Designation	Definition
3000	Operations Phase	This phase covers the operational period of the Orbital Transfer Vehicle program. In this portion of the life cycle the finished product is put into operation and is maintained in an operating condition for the duration of the program, or replaced. It includes all direct and indirect labor, materials (spares) and propellant costs required to operate and maintain the vehicles, facilities and equipment developed and produced in the DDT&E and Production Phases. The operations phase is divided into three major divisions of work: ground based operations, space based operations and logistics support.
3100	Ground Based Operations	Refers to the costs incurred in operating and providing the ground based services of: integrating the OTV into the Shuttle, tracking, command and control, vehicle recovery and maintenance of the OTV. Also includes cost of training replacement personnel and program management of the operations phase.
3110	Prelaunch	This cost element includes all material, labor and services necessary for the preflight ground operations phase of the program. In includes: (1) offline preparation (this is the installation of the payload on the OTV and checkout of the OTV and payload system), and (2) installation of the OTV and payload into the Orbiter.
3120	Command and Control	Includes cost associated with ground command, control and tracking from vehicle launch through mission completion and return. Includes such functions as flight control, telemetry communications, data processing and data analysis. Excludes those activities which are included in the standard Shuttle user charge.
3130	Post Mission Operations	This activity will involve OTV safing at space shuttle landing, removal of OTV from the space shuttle bay and flight deck at the Operational Payload Facility, moving of the OTV to the operations and checkout building for postmission processing which includes maintenance, disassembly, and refurbishment storage, or shipping as appropriate.

Table 2.3-4 Operations Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
3140	Maintenance and Refurbishment	This element refers to the labor and overhead costs for maintaining the OTV, OTV support hardware and OTV facilities in an operating condition. Includes both the recurring scheduled and unscheduled maintenance costs for the vehicle, ASE, GSE and Facilities. This element also summarizes the efforts for refurbishing and restoring the reusable OTV to a readiness condition. Cost of material and replacement parts is included under Cost Element 3141.
3141	Vehicle	This element refers to the cost of performing regular scheduled maintenance and major overhaul at specified intervals on the OTV subsystems. Also includes the cost of unscheduled, or unplanned, maintenance or servicing to return the OTV to an operable condition. Cost of replacement parts is covered under Cost Element 3310.
3142	ASE	This element refers to the cost of performing regular scheduled maintenance and unscheduled, or unplanned, maintenance for the airborne support equipment. Cost of replacement parts is covered under Cost Element 3130.
3143	GSE	This element refers to the cost of maintaining the OTV ground support equipment in an operable condition. Includes the cost of both scheduled and unscheduled maintenance. Cost of replacement parts is included under Cost Element 3340.
3144	Facilities	This activity is the cost of the effort required to maintain the OTV facilities and equipment in good operating condition.
3150	Replacement Training	Includes the cost of training qualified flight and ground crew personnel to replace those lost by rotation or attrition in order to maintain manned at level necessary to meet flight and ground operation schedules.
3160	Engineering Support	This element consists of the costs of the sustaining engineering effort required during the operations phase. A principal effort includes engineering change to the OTV which result from system operational experience or user recommendation. The element also encompasses engineering for mission peculiar changes, software maintenance, launch support activities, and technical management.

Table 2.3-4 Operations Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
3170	Program Management	Refers to the costs associated with the management of the operations phase. Includes such items as: (1) program administration and management, including budgeting, monitor, and control; (2) planning and scheduling of flights; and (3) financial and administrative support.
3200	Space Based Operations	Refers to the operation of a space based orbital transfer vehicle. Includes all maintenance operations which are performed in space. It also includes costs of maintenance/refurbishment crew as well as the transportation costs of ferrying the crew from earth to orbit or from one orbit to another. Transportation costs of logistics support for space based Orbital Transfer Vehicles are also included.
3300	Logistics Support	Refers to the recurring costs of manufacturing and stocking spare parts and propellants during the operational phase. Does not include maintenance/refurbishment labor costs.
3310	Follow-on Spares	Includes the costs of spare parts and components produced to replenish initial spare stocks in support of OTV maintenance and overhaul, both scheduled and unscheduled.
3311	Structures	Includes the spares cost of all structural elements such as tank, shell and adapters.
3312	Thermal Control	This element refers to the spares cost for the thermal control subsystem.
3313	Avionics	This element includes all spares costs related to the avionics subsystem.
3314	Power Supply and Distribution	Includes the spares costs for the OTV power supply and distribution subsystem.
3315	Propulsion	This element includes the cost to stock spares for the OTV propulsion subsystem. It includes the main engine, propellant feed, fill and drain, and thrust vector control.
3316	Attitude Control	This element refers to the cost of spares used in the overhaul and maintenance of the attitude control subsystem.

Table 2.3-4 Operations Phase Definitions (Continued)

Cost Element Number	Cost Element Designation	Definition
3320	Propellants and Gases	Refers to the costs of propellants and gases used by the OTV fleet during the operations phase, both for prelaunch testing and for flight.
3321	Propellants	Includes propellants used for each flight plus allowance for losses and testing.
3322	Gases	Includes all gases used for each flight plus allowance for losses and testing.
3330	ASE Spares	This element refers to the cost of spare parts and components produced to support ASE maintenance and overhead in Cost Element 3142.
3340	GSE Spares	This element refers to the cost of spare parts and components produced to support GSE maintenance and overhaul in Cost Element 3143.
3400	STS User Charges	Includes all user charges associated with use of the STS in accomplishing the OTV mission
3410	Basic User Charge	This element refers to the basic charge for an STS flight of standard duration.
3420	On Orbit Stay Time Charge	This element refers to the charge per day for keeping the STS orbiter loitering in low earth orbit beyond the duration of the standard mission, waiting to return the OTV

## 2.4 Methodology

The cost methodology for developing estimates in this volume is summarized in Figure 2.4-1.

The primary tool for estimating DDT&E and production costs was the Boeing-developed Parametric Cost Model (PCM). PCM develops costs from physical hardware descriptions and program schedules and allows the integration of any known costs (or outside-generated costs, such as subcontractor or vendor estimates) into the total estimate. In this way, Boeing can assemble a program cost from the available source data.

Figure 2.4-1 is an overview of the PCM estimating method and illustrates the source, type, and level of information handled and delivered from this estimating process. As depicted, the customer establishes the scope of the program relative to quantities, program time period, WBS structure, and associated ground rules and assumptions. Contractor program planners amplify the customer-furnished directives into a design, development, fabrication, test, and spares philosophy required to support the implementation of the program. These data, along with financial information relative to labor, support, and overhead rates, are assembled on a PCM "global" level input sheet that defines the program-level constraints that the cost model will work within. To develop individual component hardware estimates, engineering and manufacturing functionals describe the components that make up the subsystems. This description requires a weight, hardware type, redundancy, hardening and circuitry-type definition and an assessment of complexity, developmental status, manufacturing process, and required quality control level. These hardware data, in conjunction with programmatic-level global inputs, are processed in the PCM cost model to generate cost estimates.

The PCM is a collection of relationships and factors, developed from Boeing's historical data base, consisting of man-hour and dollar data contained in the Executive Information System (EIS). EIS is a company-wide data bank providing raw information from which (in the case of PCM) functional man-hour estimating relationships (MER) have been derived. These MER's relate program inputs to the model's internal working logic. Each major functional

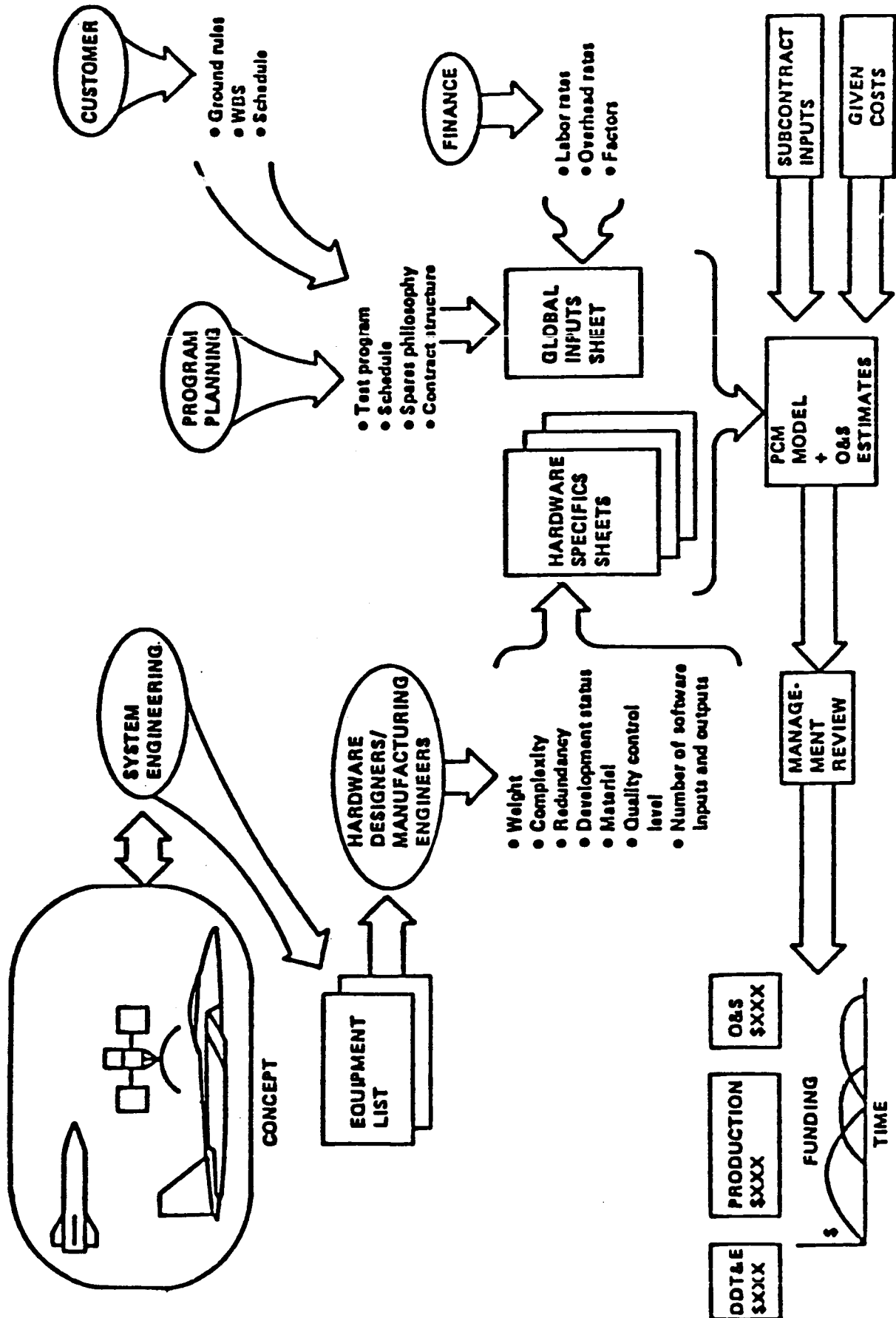


Figure 2.4-1 PCM Estimating Model

area (project engineering, developmental shop, etc.) making up Boeing's organization is represented and interrelated in the model. The functional areas are ultimately expressed in terms of man-hours required to fulfill program objectives and are converted to dollars using dollar-per-hour rates and estimating factors appropriate for the time period of the estimate.

Inputs to PCM at the program level include consideration of the following elements:

- Production quantity and rate
- Schedule - too long, too short, nominal
- Include or exclude Class I changes
- Spares as a percent of hardware produced
- Rates for engineering, developmental shop, manufacturing, quality control, tooling
- Number of recurring sets of support equipment
- Flight test program support hours
- Support levels for system engineering, software, system test, support equipment design and manufacturing, and tooling design
- Level of automation/mechanization/simplicity of end item final assembly and checkout
- Level of developmental shop support to engineering and quality assurance support to production

At the hardware level, inputs to PCM have been divided into the categories of Boeing-built, vendor-furnished "thruput," and customer-furnished thruput.

With customer-furnished thruput, costs are acknowledged and displayed but not added to the total estimate; however, related integration and system test effort is assessed and included in Boeing cost.

With vendor-furnished thruput (design and manufacture), quoted costs are carried through by PCM without change; however, required integration and system test effort related to vendor hardware is assessed and integrated into Boeing cost.

In order to estimate Boeing-built hardware, PCM considers the following elements for both design and manufacture:

- What hardware category best describes the item--mechanical, electrical, electromechanical, propulsion?
- The basic parametric measure of the hardware--in this case, weight
- The complexity factor to design/manufacture the hardware
- Program platform--space, missile, airplane, or ground hardware
- Electronics--discrete or integrated circuits
- Structural material
- Operational environment--nuclear or nonnuclear
- Hardware redundancy
- Learning curve applicable to the particular component (applies to manufacturing only)
- Extent of using new hardware and/or existing hardware with modifications
- Complexity of integrating components into system

PCM-estimated costs are all traceable back to standardized input forms, through which configuration control is maintained. These sheets specify in detail the engineering and manufacturing decisions relative to the design and manufacturing processes of each hardware component and, therefore, provide traceability of how the design has changed as it evolved.

Cost credibility is a function of (1) program and hardware definition, (2) the depth of analysis which translates this definition into PCM estimating inputs, and (3) the ability of the estimating method to convert good inputs into realistic cost estimates.

The PCM cost model has been validated with historical, actual Boeing cost data for components of all four basic hardware categories. Variance analysis has shown that the model will develop estimates within +23% at a one sigma confidence level if the inputs are accurate.

Ground rules used for determining the DDT&E and production costs are shown in Figure 2.4-2. The PCM cost inputs were based on costs generated in Reference 1, and the engine powerplant costs come from the advocate data base.

- BOEING PCM USED TO ESTIMATE DDT&E AND PRODUCTION COSTS FOR FLIGHT VEHICLES AND GSE
- AIRBORNE SUPPORT EQUIPMENT(ASE) COSTS DERIVED FROM PHASE A COSTS
- 2.75 EQUIVALANT UNITS OF TEST HARDWARE (FLT. VEHICLES AND ASE)
- 2 SETS OF GSE INCLUDED IN DDT&E
- ONE TEST FLIGHT INCLUDED IN DDT&E
- FLIGHT TEST UNITS REFURBISHED FOR OPERATIONAL FLEET
- 10% INITIAL SPARES
- 90% PRODUCTION LEARNING CURVE ON STAGES
- 95% PRODUCTION LEARNING CURVE ON ENGINES
- ENGINES/ POWERPLANT COSTS FROM ADVOCATE DATA BASE

Figure 2.4-2: DDT&E and Production Costing Groundrules

DDT&E costs for the various advanced system scenarios were developed by treating each vehicle as a brand new vehicle with no off-the-shelf components and no overlap between the chemical and advanced OTV's. This assumption was based on the fact that each vehicle is designed for different missions in the two-vehicle scenarios.

Production phase costs were estimated for all OTV's plus the SDV's and tankers in each scenario. Since the chemical and advanced stages were assumed to have no common parts, they were priced on separate learning curves.

OTV operations costs were developed from several sources, with the Phase A OTV study (Ref. 2) providing most of the ground rules. For flight-related costs, the largest item is the \$2.5M per flight charge for mission-peculiar software and data, which comes directly from the Phase A cost analysis. Other flight-related operations costs are 1.3% of theoretical first unit (TFU) costs per flight or operational spares and \$100,000 per flight to purchase propellant. Yearly costs are principally for facilities and manpower and these were assumed to be \$36M per year for the thermodynamic rockets and \$38M per year for the electrics. These costs include the charges for space-based operations, ground operations, and sustaining engineering. There is a fixed \$30M per year charge for space-based operations (maintenance, fueling, payload manifesting, etc.). This charge is the same for all concepts because all are space based, all will require turnaround in about the same length of time, and all, except the chemical ABOTV, have unique handling problems which will cause them to be remotely serviced from the LEO base.

Because no discriminators could be found between propulsion concepts with respect to LEO base manpower and because the cost of LEO base operations is still very tentative, a fixed yearly charge was assessed for operations and sustaining engineering. The difference between the yearly cost of the high-thrust rockets and the electrics is because the electrics have multiple missions flying most of the time and need extra ground support. The basic flight-related cost was \$2.75M per flight--the cost of mission software, data, spares, and propellant for the chemical ABOTV. There was an additive cost for expended equipment, which for the chemical ABOTV amounted to \$0.5M for the ballute and related hardware. For the other advanced propulsion concepts, the

basic flight-related cost was multiplied by a complexity factor to denote the estimated increase in mission complexity and spares costs. The solar ABOTV is the only other concept with expendable equipment and the \$1.3M per flight additive charge reflects the cost of the solar collector plus the ballute.

SDV operations costs were estimated to be \$22M per launch using data from Reference 1. Later data concerning the increased cost of solid propellant indicate that \$33M per launch might soon be a better number. Both launch costs were used to determine the impact. Tanker operations costs were estimated to be \$1.5M per mission. STS operations costs are dependent upon the payloads launched, which are the same for each system. A constant STS operations cost of \$1860M was estimated, assuming 64 shuttle launches would be required to support OTV operations.

#### REFERENCES

1. Davis, E. E., "Future Orbital Transfer Vehicle Technology Study," Final Report, Contract NAS1-16088, Boeing Aerospace Company, September 1981.
2. Caluori, V. A. et al, "Orbital Transfer Vehicle Concept Definition Study," Final Report, Contract NAS8-33532, Boeing Aerospace Company, D180-26090, vol. 1-6, 1980.

DOT&E	(895.0)	TFU	(30.8)
• FLIGHT HARDWARE DESIGN	(389.5)		
STRUCTURE	16.3	STRUCTURE	4.5
THERMAL CONTROL	10.2	THERM. CON	0.6
AVIONICS	32.2	AVIONICS	11.1
POWER	10.6	POWER	3.8
PROPULSION	275.0 (1)	PROPULSION	5.5
ATTITUDE CONTROL	1.2	ATT. CON.	0.9
BALLUTE	25.0	ASSY. & C/O	4.4
• SYSTEMS ENGRG. & INTEGRATION	(15.2)		
• INITIAL TOOLING	(10.3)		
• SYSTEMS TEST	(202.9)		
TEST HARDWARE	128.5		
TEST OPERATIONS	74.4		
• ASE	(11.4)		
• GSE	(18.9)		
• SOFTWARE	(19.3)		
• LIAISON/DATA	(8.2)		
• PROGRAM MANAGEMENT	(39.3)		

MILLIONS OF 1980 DOLLARS

VEHICLE CHARACTERISTICS

STARTBURN MASS	48840 kg
PROPELLANT MASS	30500 kg
BURNOUT MASS	4340 kg
VEHICLE THRUST	13200 N
(2 engines)	
ENGINE Isp	485 sec

(1) INCLUDES ADVANCED SPACE ENGINE AT \$271 M DOT&amp;E, \$1.86 M TFU

Figure 3.1-1: SB LO<sub>2</sub>/LH<sub>2</sub> OTV DDT&E and TFU Cost Estimate

DOT & E	(1048.8)	TFU	(48.4)
• FLIGHT HARDWARE DESIGN	(609.2)		
STRUCTURE	25.6	STRUCTURE	9.3
THERMAL CONTROL	14.6	THERMAL CONTROL	1.0
AVIONICS	32.2	AVIONICS	11.1
POWER	10.6	POWER	3.8
PROPULSION ▷	500	PROPULSION ▷	15
ATTITUDE CONTROL	1.2	ATTITUDE CONTROL	0.9
BALLUTE	25.0	ASSEMBLY & C/O	5.3
• SYSTEMS ENGRG. & INTEGRATION	33.5		
• INITIAL TOOLING	18.0		
• SYSTEMS TEST			
TEST HARDWARE	127.6		
TEST OPERATIONS	129.8		
• ASE	12.0		
• GSE	31.4		
• SOFTWARE	32.1		
• LIAISON DATA	18.8		
• PROGRAM MANAGEMENT	44.4		

MILLIONS OF 1980 DOLLARS

VEHICLE CHARACTERISTICS

STARTBURN MASS	39720 kg
PROPELLANT MASS	18860 kg
BURNOUT MASS	8550 kg
ENGINE THRUST POWER	460 mw
ENGINE Isp	1050 sec

▷ COST FROM LA-5044-MS VOL. III (1972) UPDATED TO 1980

▷ ENGINE COST \$9M

Figure 3.1-2: Rotating-Bed Rocket DDT&amp;E and TFU Cost Estimate

<u>DDT &amp; E</u>	(\$612.9M)	<u>TFU</u>	\$34 M
• FLIGHT HARDWARE DESIGN	(311.8)		
STRUCTURE	14.8	STRUCTURE	4.3
THERMAL CONTROL	11.8	THERMAL CONTROL	0.7
AVIONICS	32.2	AVIONICS	11.1
POWER	12.8	POWER	6.0
PROPULSION $\triangleright$	239	PROPULSION $\triangleright$	7.0
ATTITUDE CONTROL	1.2	ATTITUDE CONTROL	0.9
• SYSTEMS ENGRG. & INTEGRATION	16.8	ASSEMBLY & C.O.	4.0
• INITIAL TOOLING	13.3		
• SYSTEMS TEST			
TEST HARDWARE	93.5		
TEST OPERATIONS	80.4		
• ASE	12		
• GSE	21.2		
• SOFTWARE	22.4		
• LIAISON DATA	8.1		
• PROGRAM MANAGMENT	33.4		
			MILLIONS OF 1980 DOLLARS
		<u>VEHICLE CHARACTERISTICS</u>	
		STARTBURN MASS	25300 kg
		PROPELLANT MASS	8320 kg
		BURNOUT MASS	4740 kg
		ENGINE THRUST POWER	15 MW
		ENGINE Isp	1500 sec

$\triangleright$  INCLUDES \$25 M FOR DEVELOPMENT OF LIGHTWEIGHT RECIEVER, \$10M FOR POINTER TRACKER , AND \$200 M FOR LASER ENGINE  
 $\triangleright$  INCLUDES \$0.5 M FOR RECIEVER , \$2.0 M FOR POINTER/TRACKER & \$2.5 M FOR LASER ENGINE

Figure 3.1-3: Space-Based Laser OTV DDT&amp;E and Cost Estimate

<u>DDT &amp; E</u>	(863.6)	<u>TFU</u>	(401)
• FLIGHT HARDWARE DESIGN	(520.4)		
STRUCTURE	20.0	STRUCTURE	6.5
THERMAL CONTROL	14.2	THERMAL CONTROL	1.0
AVIONICS	32.2	AVIONICS	11.1
POWER	12.8	POWER	6.0
PROPULSION $\triangleright$	440	PROPULSION $\triangleright$	10.0
ATTITUDE CONTROL	1.2	ATTITUDE CONTROL	0.9
• SYSTEMS ENGRG. & INTEGRATION	18.0	ASSEMBLY & C.O.	4.6
• INITIAL TOOLING	16.0		
• SYSTEMS TEST			
TEST HARDWARE	110.3		
TEST OPERATIONS	84.4		
• ASE	12.0		
• GSE	22.9		
• SOFTWARE	24.0		
• LIAISON DATA	8.9		
• PROGRAM MANAGMENT	36.7		
			MILLIONS OF 1980 DOLLARS
		<u>VEHICLE CHARACTERISTICS</u>	
		STARTBURN MASS	31200 kg
		PROPELLANT MASS	12200 kg
		BURNOUT MASS	6670 kg
		ENGINE THRUST POWER	80 MW
		ENGINE Isp	1500 sec

$\triangleright$  INCLUDES \$10 M TRACKER, \$25 M RECIEVER, \$250 M LASER THRUSTER & \$150 M SOLAR THRUSTER  
 $\triangleright$  INCLUDES \$2 M TRACKER, \$1.0 M RECIEVER, \$2.5 M LASER THRUSTER & \$2 M SOLAR THRUSTER

Figure 3.1-4: Ground-Based Laser DDT&amp;E and TFU Cost Estimate

COMPONENT	MASS	FLIGHT HARDWARE DESIGN & DEV	HARDWARE UNIT COST	
• ELECTRIC POWER PLANT				
RBR POWERPLANT & SHIELD	10 MT	500	100	
• RADIATOR SYSTEM	70 MT	125	14	\$200 /kg
POWER PROCESSING	15 MT	27	78	SEPS PPU
• FEL SUBSYSTEM		(150)	(30)	BOM
KLYSTRONS & E OPTICS	6 MT			
CAVITY & COOLING	15 MT			
• 30 METER OPTICS + STABILITY & CONTROL	75 MT	(400)	(30)	LOCKHEED
• GROWTH (15 %)	19 MT	50	10	
	220 MT	\$1250 M	\$262 M	
OPS COST				
4 SDV LAUNCHES = \$ 88 M				
3 STS LAUNCHES = \$ 87 M				
		1990 DOLLARS		

Figure 3.1-5: 3-MW Space-Based Laser Cost Estimate

DOT&E (2185)	TFU (301)
• FLIGHT HARDWARE 1250	FLIGHT HARDWARE 262
• SYSTEM ENGR & INTEG. 225	ASSEMBLY & C/O 39
• TOOLING 20	
• SYSTEM TEST 300	
• SOFTWARE 86	MILLIONS OF 1980 DOLLARS
• LAISON 25	
• PROGRAM MANAGEMENT 125	
• LAUNCH OPS 88	
• FLIGHT OPS 87	

Figure 3.1-6: 3-MW Space-Based Laser DDT&amp;E Cost Estimate

	MASS	FLIGHT HARDWARE DESIGN & DEV.	HARDWARE UNIT COST
<b>ELECTRIC POWER PLANT</b>			
SOLAR ARRAY (13500 m <sup>2</sup> )	418 MT	785	550
POWER PROCESSING	115 MT	75	30
LASER & CAVITY OPTICS	185 MT	200	25
30 METER OPTICS + STABILITY & CONTROL	75 MT	400	30
OTHER	2 MT	30	15
	<u>793 MT</u>	<u>\$1490 M</u>	<u>\$850 M</u>
<b>OPS COST</b>			
14 SDV LAUNCHES - \$308 M			
8 STS LAUNCHES - \$232 M			


Figure 3.1-7: 25-MW Space-Based Laser Cost Estimate

<b>DDT&amp;E (2487)</b>		<b>IFU (730)</b>	
• FLIGHT HARDWARE	(1490)		
POWER GENERATION	785	POWER GENERATION	550
POWER PROCESSING	75	POWER PROCESSING	30
LASER SYSTEM	200	LASER SYSTEM	25
TRANSMITTER SYSTEM	400	TRANSMITTER SYSTEM	30
OTHER	30	OTHER	15
• SYSTEM ENGR & INTEG.	105	ASSEMBLY & C/O	80
• TOOLING	50		
• SYSTEM TEST	175		
• SYSTEM GSE	130		
• SOFTWARE	140		
• LIASON	28		
• PROGRAM MANAGEMENT	117		
• FLIGHT OPS	232		

Figure 3.1-8: 25-MW Space-Based Laser DDT&amp;E Cost Estimate

DOT & E	(777.8)	TFU	(33.8)
• FLIGHT HARDWARE DESIGN	(448.6)	STRUCTURE	6.1
STRUCTURE	19.0	THERMAL CONTROL	0.9
THERMAL CONTROL	13.4	AVIONICS	11.1
AVIONICS	32.2	POWER	6.0
POWER	12.8	PROPULSION	4.2
PROPULSION	34.5	ATTITUDE CONTROL	0.9
ATTITUDE CONTROL	1.2	ASSEMBLY & C.O.	4.0
BALLUTE	25.0		
• SYSTEMS ENGRG. & INTEGRATION	20.2		
• INITIAL TOOLING		MILLIONS OF 1980 DOLLARS	
• SYSTEMS TEST	14.7		
TEST HARDWARE	93.0	VEHICLE CHARACTERISTICS	
TEST OPERATIONS	90.0	STARTBURN MASS	30300 kg
• ASE	11.2	PROPELLANT MASS	11650 kg
• GSE	25.6	BURNOUT MASS	5380 kg
• SOFTWARE	26.9	ENGINE THRUST POWER	2.3 kg
• LIAISON DATA	9.1	ENGINE Isp	1100 sec
• PROGRAM MANAGMENT	37.5		
▶ INCLUDES 1500 lb <sub>f</sub> LOX-LH <sub>2</sub> ENGINE AT \$164M AND SOLAR COLLECTOR AT \$27 M			
▶ INCLUDES 1500 lb <sub>f</sub> LOX-LH <sub>2</sub> ENGINE AT \$0.8 M AND SOLAR COLLECTOR AT \$0.8 M			

**Figure 3.1-9: Solar Thermal Rocket DDT&E and TFU Cost Estimate**

COMPONENT	MASS	FLIGHT HARDWARE DESIGN & DEV. COST	HARDWARE UNIT COST	UNIT COST ESTIMATING RELATIONSHIP
POWER ARRAY (445 kwe GaAs)	1600	100 	51	\$PS/SEPS/FOTV
ELECTRIC PROPULSION SYSTEM	(1060)	(18)	(12)	
THRUSTERS (16)	230	1.4	4.5	\$0.4 M TFU x 0.710
PPU (DIRECT DRIVE)	500	4.8	6.8	\$ 0.6 M TFU x 0.710
TCU	100	2.6	0.1	\$4000/kg
STRUCTURE	120	4.4	0.2	\$2000/kg
TANKAGE	100	2.6	0.1	\$1000/kg
AVIONICS	(700)	(32)	(10)	FOTV
OTHER	360	(12)	(6)	FOTV
TOTAL	3700 kg	\$162 M	\$79 M	

**▷ DDT& E COST**

1980 DOLLARS

### 3.1-10 Advanced Solar Photovoltaic-Ion Cost Estimate

COMPONENT	MASS	FLIGHT HARDWARE DESIGN & DEV.	HARDWARE UNIT COST	COST ESTIMATING RELATIONSHIP
<u>POWER SOURCE</u>		(48)	(18)	
CONCENTRATOR	300	12	0.5	\$300/M <sup>2</sup> + \$250k
CAVITY/RERADIATOR	470	10	4.5	\$9,000/kg + \$300 k/m <sup>2</sup> (structure) (solar cells)
RADIATORS	3230	27	13	\$4000/kg
<u>ELECTRIC PROPULSION SYSTEM</u>	(1740)	(24)	(17)	SPS/SEPS/FOTV
THRUSTERS (14)	210	1.4	4.0	\$0.4 M TFU x 0.718
PPU	1000	7.1	11.8	\$1.17 M TFU x 0.718
TCU	200	6.7	0.8	\$4000/kg
STRUCTURE	210	5.9	0.2	\$1000/kg
TANKAGE	120	2.9	0.1	\$1000/kg
<u>AVIONICS</u>	(510)	(35)	(10)	FOTV
OTHER	800	(12)	(5)	FOTV
<b>TOTAL</b>	<b>6850 kg</b>	<b>\$119 M</b>	<b>\$50 M</b>	<b>1980 DOLLARS</b>

## 3.1-11 SPV-Ion DDT&amp;E and TFU Cost Estimate

DDT & E	(520)	TFU	(107)
• FLIGHT HARDWARE	(162)		
POWER GENERATION	100	POWER GENERATION	58.4
THRUSTERS	1.4	THRUSTERS	6.3
PPU	4.8	PPU	9.0
STR, TANK & TCU	11.8	STR, TANK & TCU	0.7
AVIONICS	32	AVIONICS	12
OTHER (RCS & EPS)	12	OTHER	6
• SYSTEM ENGRG. & INTEG.	14	ASSEMBLY & C/O	14.0
• TOOLING	6		
• SYSTEMS TEST			
TEST HARDWARE	194		
TEST OPERATIONS	58		
• ASE	12		
• GSE	12		
• SOFTWARE	19		
• LIAISON/DATA MANAG.	8		
• PROGRAM MANAGEMENT	35		
		MILLIONS OF 1980 DOLLARS	
		<u>VEHICLE CHARACTERISTICS</u>	
		STARTBURN MASS	17800 kg
		PROPELLANT MASS	2310 kg
		BURNOUT MASS	3700 kg
		ENGINE THRUST POWER	313 kw
		ENGINE Isp	6000 sec.

## 3.1-12 Thermophotovoltaic-Ion OTV Cost Estimate

DOT & E	(480)	TFU	(70)
• FLIGHT HARDWARE	(119)		
POWER GENERATION	48	POWER GENERATION	20.6
THRUSTERS	1.4	THRUSTERS	5.6
PPU	7.1	PPU	16.4
STR, TANK & TCU	18.5	STR, TANK & TCU	1.4
AVIONICS	35	AVIONICS	12
OTHER (RCS & EPS)	12	OTHER	5
• SYSTEM ENGRG. & INTEG.	18	ASSEMBLY & C/O	9.0
• TOOLING	19		
• SYSTEMS TEST		<u>VEHICLE CHARACTERISTICS</u>	
TEST HARDWARE	133	STARTBURN MASS	21640 kg
TEST OPERATIONS	84	PROPELLANT MASS	2790 kg
• ASE	12	BURNOUT MASS	6850 kg
• GSE	23	ENGINE THRUST POWER	219 kw
• SOFTWARE	24	ENGINE Isp	6000 sec.
• LIAISON	10		
• PROGRAM MANAGEMENT	38		

## 3.1-13 TPV-Ion DDT&amp;E and TFU Cost Estimate

COMPONENT	MASS	FLIGHT HARDWARE DESIGN & DEV. COST	HARDWARE UNIT COST	UNIT COST ESTIMATING RELATIONSHIP
NUCLEAR POWER SOURCE [ 374 kwe α = 20 kg/kwe ]	(7480)	▷ (400)	(40)	DAVE BUDEN (LASL) 100 kwe NPS DDT&E = \$390 M UNIT COST = \$15 M α = 16.4 kg/kwe
<u>ELECTRIC PROPULSION SYSTEM</u>	(2100)	(26)	(22)	SPS/SEPS/FOTV
THRUSTERS (18)	250	1.4	5.1	\$0.4 M TFU x 0.703
PPU	1200	7.1	14.8	\$1.17 M TFU x 0.703
TCU	240	7.4	1.6	\$4000/kg x 2
STRUCTURE	250	6.4	0.3	\$1000/kg
TANKAGE	180	3.7	0.2	\$1000/kg
<u>AVIONICS</u>	(510)	(35)	(10)	FOTV
<u>OTHER</u>	(600)	(12)	(5)	FOTV
TOTAL	10,700 kg	\$473 M	\$77 M	1980 DOLLARS

▷ DDT &amp; E COST

## 3.1-14 Nuclear Thermoelectric-Ion OTV Cost Estimate

DDT & E	(938)	TFU	(120)
• FLIGHT HARDWARE	(473)		
POWER GENERATION	400	POWER GENERATION	46
THRUSTERS	1.4	THRUSTERS	7.3
PPU	7.1	PPU	21.1
STR, TANK & TCU	17.5	STR, TANK & TCU	2.8
AVIONICS	36	AVIONICS	12
OTHER (RCS&EPS)	12	OTHER	5
• SYSTEM ENGRG. & INTEG.	22	ASSEMBLY & C/O	26.8
• TOOLING	30		
• SYSTEMS TEST		<u>VEHICLE CHARACTERISTICS</u>	
TEST HARDWARE	216	STARBUrn MASS	28340 kg
TEST OPERATIONS	96	PROPELLANT MASS	3640 kg
• ASE	12	BURNOUT MASS	10700 kg
• GSE	21	ENGINE THRUST POWER	283 kw
• SOFTWARE	22	ENGINE Isp	8000 sec
• LIAISON	11		
• PROGRAM MANAGMENT	43		

## 3.1-15 NPS-Ion DDT&amp;E and TFU Cost Estimate

	CHEMICAL ABOTV	NUCLEAR RBR	SPACE-BASED LASER	GROUND BASED LASER	SOLAR ABOTV
• STAGES					
• ADVANCED OTV's					
FLEET SIZE	2	2	2	2	2
PLANETARY FLIGHTS	8	8	-	8	8
WEAROUT	-	-	6	-	-
• CHEMICAL OTV's					
MANNED OTV's	-	-	2	2	2
PLANETARY FLIGHTS	-	-	8		
• ENGINES					
• ADVANCED PROPULSION (10 FLIGHTS/ENGINE)	-	22 + 2*	8 + 2*	15 + 2*	15 + 2*
• CHEMICAL (20 FLIGHTS/ENGINE)	22 + 2*	-	22 + 2*	6 + 2*	6 + 2*
*SPARES					

## 3.1-16 Production Quantities for High-Thrust Concepts

● STAGES	SPV-ION	TPV-ION	NPS-ION
● ELECTRIC OTV's (10 MISSION LIFETIME)			
FLEET SIZE	5	5	5
PLANETARY FLIGHTS	8	8	8
WEAROUT	2	2	2
● CHEMICAL OTV's (40 MISSION LIFETIME)			
MANNED OTV's	2	2	2
PLANETARY FLIGHTS	-	-	-
● ENGINES			
ION (10 FLIGHTS/ENGINE)	240+32*	210+28*	270+36*
CHEMICAL (20 FLIGHTS/ENGINE)	8+2*	8+2*	8+2*

\*SPARES

## 3.1-17 Production Quantities for Low-Thrust Concepts

DOT & E COSTS	CHEMICAL ABOTV	NUCLEAR RBR	SPACE-BASED LASER	GROUND-BASED LASER	SOLAR ABOTV
ADVANCED OTV's	-	1060	615	855	780
CHEMICAL SUPPORT OTV's	695	-	695	695	695
SUPPORT SYSTEMS	-	100	2465 (25 MW FEL)	530 (200 MW EDL)	-
<b>PRODUCTION COSTS</b>					
ADVANCED OTV's	-	1000	365	570	445
CHEMICAL SUPPORT OTV's	375	-	375	90	90
PECULIAR SUPPORT SYSTEMS	-	30	955	-	-
TOTAL	1070	2180	5460	2740	2010

COSTS IN MILLIONS OF 1980 DOLLARS

## 3.1-18 High-Thrust System Acquisition Costs

	SPV-ION	TPV-ION	NPS-ION
<b>DOT &amp; E COSTS</b>			
ADVANCED OTV's	520	480	946
CHEM SUPPORT OTV's	695	695	695
SUPPORT SYSTEMS	-	-	100
<b>PRODUCTION COSTS</b>			
ADVANCED OTV's (16)	1755	1125	1875
SUPPLEMENTARY CHEM OTV's (2)	90	90	90
SUPPORT SYSTEMS	-	-	30
<b>TOTAL ACQUISITION COST</b>	<b>3060</b>	<b>2390</b>	<b>3736</b>

COST IN MILLIONS OF 1980 DOLLARS

## 3.1-19 Low-Thrust System Acquisition Costs

APCS-284		CHEMICAL ABOTV	NUCLEAR RBR	SPACE-BASED LASER OTV	GROUND-BASED LASER OTV	SOLAR ABOTV	SPV ION	TPV ION	NPS ION
<u>YEARLY COSTS</u>									
\$30 M/YR	SPACE-BASED OPERATIONS	480	480	480	480	480	480	480	480
\$6-8 M/YR	GROUND SUPPORT	95	95	95	95	95	130	130	130
<u>FLIGHT RELATED COSTS</u>									
\$2.75 M/YR	FLIGHT OPS + EXPENDABLES	720 (1x+0.5)	1220 (2.0x)	850 (1.5x)	855 (1.5x)	930 (1.2x +1.3)	855 (1.5x)	815 (1.4x)	1070 (2.0x)
<b>TOTAL OTV OPS COSTS</b>		<b>1295</b>	<b>1795</b>	<b>1425</b>	<b>1430</b>	<b>1505</b>	<b>1465</b>	<b>1425</b>	<b>1680</b>

COST IN MILLIONS OF 1980 DOLLARS

## 3.1-20 OTV Operations Costs - Low Model

### 3.0 SUMMARY COST PRESENTATION

This section summarizes the life cycle costing of the eight mission scenarios corresponding to the low mission model and the five mission scenarios corresponding to the high mission model. The cost estimation has been divided into two subsections: relative total life cycle cost estimates for the low model are in section 3.1; section 3.2 covers the life cycle cost estimates for the high model.

#### 3.1 Low Model Life Cycle Costs

System Acquisition Costs - The system acquisition costs are the DDT&E and production costs for each of the vehicle types involved in a particular scenario. For the scenarios examined here, the vehicles usually required were: (1) the chemical ABOTV used for the manned portion of the mission model; (2) the advanced propulsion vehicle used for the delivery and planetary missions; (3) the reusable shuttle-derivative vehicles used to launch the vehicles, equipment, and propellant tankers into LEO; and (4) the tanker vehicles used to carry propellants into LEO.

DDT&E and TFU costs for each OTV type and two sizes of space-based laser are presented in Figures 3.1-1 through 3.1-15. The methodology used was discussed in the previous section and assumptions are shown on each figure. Note that the test hardware for the electric vehicles was equivalent to only 1 TFU and not 2.75 TFU's as assumed for the thermodynamic rockets (this is because of the modular test approach possible with electric vehicles). The data are arranged in the same format and with the same headings as the WBS presented earlier.

Production costs were estimated using the production quantities shown in Figures 3.1-16 and 3.1-17 and the production learning curves shown in Figure 2.4-2. The resultant system acquisition costs for the various OTV's and their individual support systems are shown in Figures 3.1-18 and 3.1-19. These do

QTV SYSTEMS	SPACE BASED CHEMICAL ABOTV	NUCLEAR ROTATING BED ROCKET	SPACE BASED LASER + COTV	GROUND BASED LASER + COTV	SOLAR THERMAL ROCKET + COTV
DDT&E	695	1150	3775	2080	1475
PRODUCTION	365	1030	1685	660	535
OPERATIONS	<u>1295</u>	<u>1795</u>	<u>1425</u>	<u>1430</u>	<u>1505</u>
	2355	3975	6885	4170	3515
<u>TANKER</u>					
DDT&E	215	310	410	410	410
PRODUCTION	100	80	130	130	130
OPERATIONS	<u>200</u>	<u>125</u>	<u>35</u>	<u>55</u>	<u>55</u>
	515	515	575	595	595
<u>SDV/RPS</u>					
DDT&E	1100	1100	1100	1100	1100
PRODUCTION	450	450	450	450	450
OPERATIONS	<u>3080</u>	<u>2155</u>	<u>2070</u>	<u>1935</u>	<u>1890</u>
	4630	3705	3620	3485	3440
<u>SIS</u>					
DDT&E	-	-	-	-	-
PRODUCTION	-	-	-	-	-
OPERATIONS	<u>1860</u>	<u>1860</u>	<u>1860</u>	<u>1860</u>	<u>1860</u>
TOTAL LCC	9360	10055	12940	10110	9410

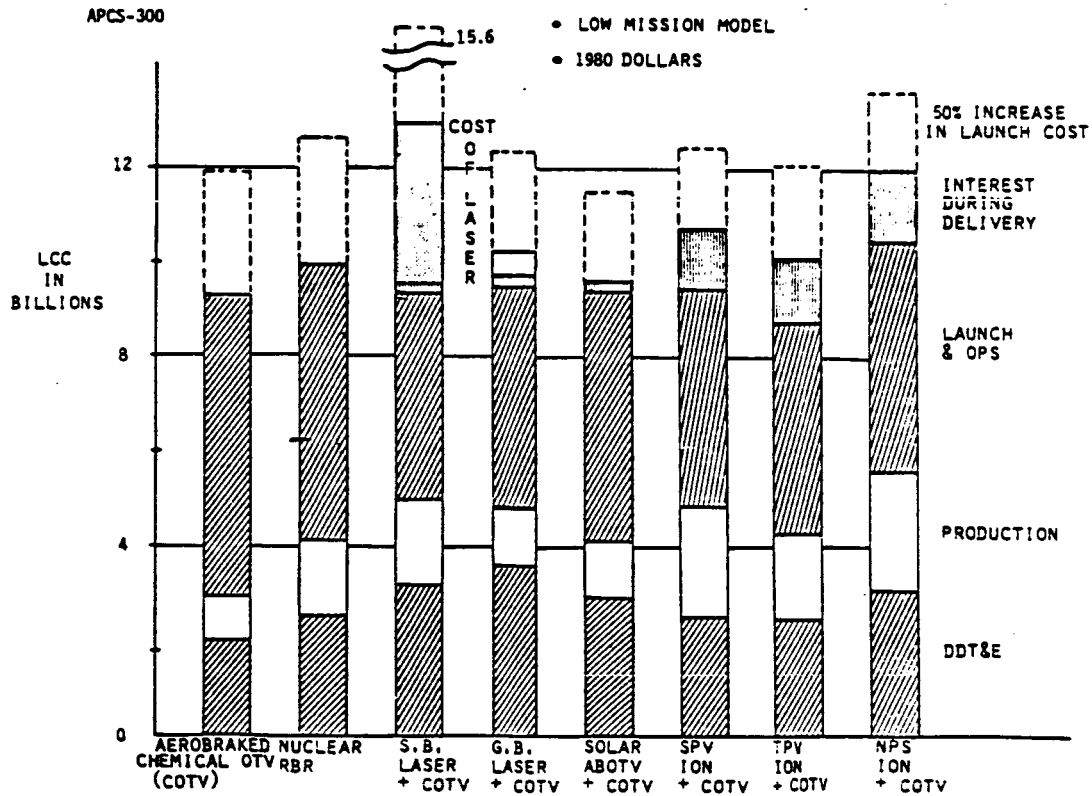
COST IN MILLIONS OF 1980 DOLLARS

### 3.1-21 Life Cycle Cost Summary by Hardware Element - High-Thrust Concepts

QTV SYSTEMS	SPV-10N + COTV	TPV-10N + COTV	NPS-10N + COTV
DDT&E	1215	1175	1740
PRODUCTION	1845	1215	1995
OPERATIONS	<u>1465</u>	<u>1425</u>	<u>1680</u>
	4525	3815	5415
<u>SDV/RPS</u>			
DDT&E	1100	1100	1100
PRODUCTION	450	450	450
OPERATIONS	<u>1165</u>	<u>1210</u>	<u>1255</u>
	2715	2760	2805
<u>COTV TANKER</u>			
DDT&E	215	215	215
PRODUCTION	70	70	70
OPERATIONS	<u>65</u>	<u>-65</u>	<u>65</u>
	350	350	350
<u>SIS</u>			
DDT&E	-	-	-
PRODUCTION	-	-	-
OPERATIONS	<u>1860</u>	<u>1860</u>	<u>1860</u>
TOTAL LCC	9450	8785	10430

COST IN MILLIONS OF 1980 DOLLARS

### 3.1-22 Life Cycle Cost Summary by Hardware Element - Low-Thrust Concepts



3.1-23 Life Cycle Cost Summary Chart

DDT&E (342.4)

• FLIGHT HARDWARE DESIGN	(83)
PROPULSION	30
AVIONICS	3
OTHER	50
• SYSTEM ENGR. & INTEGRATION	8
• INITIAL TOOLING	12.1
• TEST HARDWARE	121.9
• TEST OPERATIONS	53.4
• ASE	12
• GSE	10
• SOFTWARE	10.6
• LIAISON/DATA	6.1
• PROGRAM MANAGEMENT	25.3

TFU (34.5)

PROPULSION	7.5
AVIONICS	12
OTHER	11
ASSY&c/o	4

VEHICLE CHARACTERISTICS

STARTBURN MASS	185400 kg
PROPELLANT MASS	113400 kg
BURNOUT MASS	2X(5120) kg
ENGINE THRUST	2X(198000)N
ENGINE Isp	485 sec.

MILLIONS OF 1980 DOLLARS

3.2-1 Large Chemical ABOTV DDT&amp;E and TFU Cost Estimate

not include the DDT&E and production costs of the shuttle-derivative launch vehicles or the tankers. These numbers were calculated separately, using data obtained from Reference 1, and are shown in the LCC summaries.

Operations Costs - Operations cost estimates for the low mission model are summarized in Figure 3.1-20. The methodology used has already been discussed and is summarized in the figure.

Life Cycle Costs - Life cycle costs are the combined total of DDT&E, production, and operations costs over the 16 years of the mission model. Summaries of the life cycle cost estimates divided into hardware elements are shown in Figures 3.1-21 and 3.1-22. Note that these cost estimates include the costs of developing and producing the shuttle-derivative vehicles and the propellant tankers as well as the OTV's.

Life cycle costs for the low model are summarized in Figure 3.1-23. Costs are those shown in the previous figures except interest charges during delivery have been added. Interest charges were calculated by (1) adding the cost of the payload (assumed to average \$100M) to the launch costs of the payload and propellants and to the cost of the propellants themselves and (2) then determining the interest accrued (at 15% annual interest) on this amount during the LEO to GEO delivery time. This interest cost is equivalent to the interest paid by a user on the money invested at the time of launch until the time the payload is deployed and begins earning revenue. The interest costs over the life of the mission model vary from negligible for the high-thrust concepts (which deliver in 1/2 day) to \$1.5B for the NPS-ion vehicle (which requires 220 days). Also shown in Figure 3.1-23 is the increase in LCC if launch costs increase 50% as expected.

### 3.2 High Model Life Cycle Costs

LCC's for the high model were calculated in the same manner, using the same rules as LCC's for the low model. In fact, the high model contains the low model as a subset and thus can be incremented from it by adding the large vehicles and extra missions required.

<u>DDT&amp;E</u> (478.7)		<u>TFU</u> (51.)	
● FLIGHT HARDWARE DESIGN	(113)		
PROPULSION	50	PROPULSION	15
AVIONICS	3	AVIONICS	12
OTHER	60	OTHER	18
● SYSTEM ENGR. & INTEGRATION	19	ASSEMBLY SC/O	6
● INITIAL TOOLING	24.8		
● TEST HARDWARE	171.8	VEHICLE CHARACTERISTICS	
● TEST OPERATIONS	58	STARTBURN MASS	122500 kg
● ASE	12	PROPELLANT MASS	50100 kg
● GSE	18	BURNOUT MASS	11760 kg
● SOFTWARE	19	ENGINE THRUST POWER	460 MW
● LIAISON/DATA	8.4	ENGINE Isp	1050 sec.
● PROGRAM MANAGEMENT	34.7		
		MILLIONS OF 1980 DOLLARS	

## 3.2-2 Large Nuclear RBR DDT&amp;E and TFU Cost Estimate

<u>DDT&amp;E</u> (527.7)		<u>TFU</u> (48.0)	
● FLIGHT HARDWARE DESIGN	(175)		
PROPULSION	100	PROPULSION ▷	11.9
AVIONICS	3	AVIONICS	12
OTHER	72	OTHER	18.6
● SYSTEM ENGR. & INTEGRATION	11.3	ASSEMBLY & c/o	5.5
● INITIAL TOOLING	30.7		
● TEST HARDWARE	162.9		
● TEST OPERATIONS	63.5		
● ASE	12		
● GSE	14.3		
● SOFTWARE	15		
● LIAISON/DATA	8.4		
● PROGRAM MANAGEMENT	34.6		

## 3.2-3 Large Solar ABOTV DDT&amp;E and TFU Cost Estimate

<u>DDT&amp;E</u> (493.3)		<u>TFU</u> (228)	
● FLIGHT HARDWARE DESIGN	(64)	PROPULSION ▷	180
PROPULSION	22	AVIONICS	12
AVIONICS	3	OTHER	8
OTHER	39	ASSEMBLY & C/O	26
● SYSTEM ENGR. & INTEGRATION	6.3		
● INITIAL TOOLING	30.6		
● TEST HARDWARE	268.3	▷ \$45/WATT SOLAR ARRAY	
● TEST OPERATIONS	48.3	(@ 5/YEAR PRODUCTION RATE)	
● ASE	12	\$1M TFU THRUSTER + PPU	
● GSE	8		
● SOFTWARE	8.4		
● LIAISON/DATA	9.2		
● PROGRAM MANAGEMENT	38.2		

## 3.2-4 Large SDV-Ion DDT&amp;E and TFU Cost Estimate

<u>DDT&amp;E</u> (460)		<u>TFU</u> (148)	
● FLIGHT HARDWARE DESIGN	(91)	PROPULSION ▷	109
PROPULSION	32	AVIONICS	12
AVIONICS	3	OTHER	10
OTHER	56	ASSEMBLY & C/O	17
● SYSTEM ENGR. & INTEGRATION	8.9		
● INITIAL TOOLING	45.5		
● TEST HARDWARE	180.3		
● TEST OPERATIONS	56.1		
● ASE	12		
● GSE	11.2		
● SOFTWARE	11.8		
● LIAISON/DATA	8.4		
● PROGRAM MANAGEMENT	34.6		

MILLIONS OF 1980 DOLLARS	
▷ PROPULSION TFU	
\$3.0	CONCENTRATOR
\$11.5	CAVITY & RERADIATOR
\$4.5	RADIATORS (\$200/kg)
\$90	THRUSTERS & PPUS
	(DIRECT DRIVE)

## 3.2-5 Large TPV-Ion DDT&amp;E and TFU Cost Estimate

	CHEMICAL ABOTV	NUCLEAR RBR	SOLAR ABOTV	SPV ION	TPV ION
<b>STAGES</b>					
<b>ADVANCED OTV'S</b>					
FLEET SIZE	4	2	2	5	5
WEAR OUT	16	18	18	35	35
CHEMICAL OTV'S FOR ADDITIONAL MANNED MISSIONS	1	—	1	1	1
<b>ENGINES</b>					
ADVANCED PROPULSION (10 FLIGHTS/ENGINE)	—	38 + 2*	38 + 2*	3040	3600
CHEMICAL (20 FLIGHTS/ENGINE)	114	2	2	2	2
* SPARES					

## 3.2-6 Production Quantities for Vehicles Unique to High Model

<u>DDT&amp;E COSTS</u>	<u>CHEMICAL ABOTV</u>	<u>NUCLEAR RBR</u>	<u>SOLAR ABOTV</u>	<u>SPV ION</u>	<u>TPV ION</u>
LOW MODEL OTVS (ADV. & COTVS)	695	1150	1475	1215	1175
NEW HIGH MODEL OTVS	<u>340</u> 1035	<u>480</u> 1630	<u>530</u> 2005	<u>495</u> 1710	<u>460</u> 1635
<u>PRODUCTION COSTS</u>					
LOW MODEL ADVANCED OTVS	375	1000	445	1755	1125
HIGH MODEL ADVANCED OTVS	860	1890	1335	6680	5360
CHEMICAL SUPPORT OTVS	<u>-</u> 1235	<u>-</u> 2890	<u>135</u> 1915	<u>135</u> 8570	<u>135</u> 6620

MILLIONS OF 1980 DOLLARS

## 3.2-7 High Model Systems Acquisition Costs

	CHEMICAL ABOTV	NUCLEAR RBR OTV	SOLAR ABOTV +COTV	SPV-ION + COTV	TPV-ION + COTV
<u>YEARLY COSTS (1995-2004)</u>					
\$30 M/YR SPACE-BASED OPS	300	300	300	300	300
\$6-8 M/YR GROUND SUPPORT	60	60	60	80	80
<u>YEARLY COSTS (2005-2010)</u>					
\$150 M/YR SPACE-BASED OPS	750	750	750	750	750
\$30-40 M/YR GROUND SUPPORT	180	180	180	240	240
<u>FLIGHT RELATED COSTS</u>					
LOW MODEL VEHICLES	720	1220	1020	1050	1050
\$2.75 M/FLIGHT + EXPENDABLES	(1x+0.5)	(2.0x)	(1.2x+1.3)	(1.5x)	(1.5x)
HIGH MODEL VEHICLES	2850	2470	2850	2140	2140
\$3.25 M/FLIGHT + EXPENDABLES	(2x+1.0)	(2.0x)	(1.2x+3.6)	(1.5)	(1.5)
TOTAL OTV OPS COSTS	4860	4980	5160	4560	4560

COSTS IN MILLIONS OF 1980 DOLLARS

## 3.2-8 OTV Operations Costs - High Model

	CHEM ABOTV	NUC RBR	SOLAR ABOTV	SPV ION	TPV ION
CAPITAL COST, \$M	205	165	160	140	145
$\Delta T$ , DAYS	0.5	1.0	24	180	180
INTEREST COST, \$M PER FLIGHT	.039	0.063	1.477	9.990	10.346
HIGH MODEL, \$M INTEREST COST	-	3.5	167	1242	1466

## 3.2-9 Interest Costs - High Model

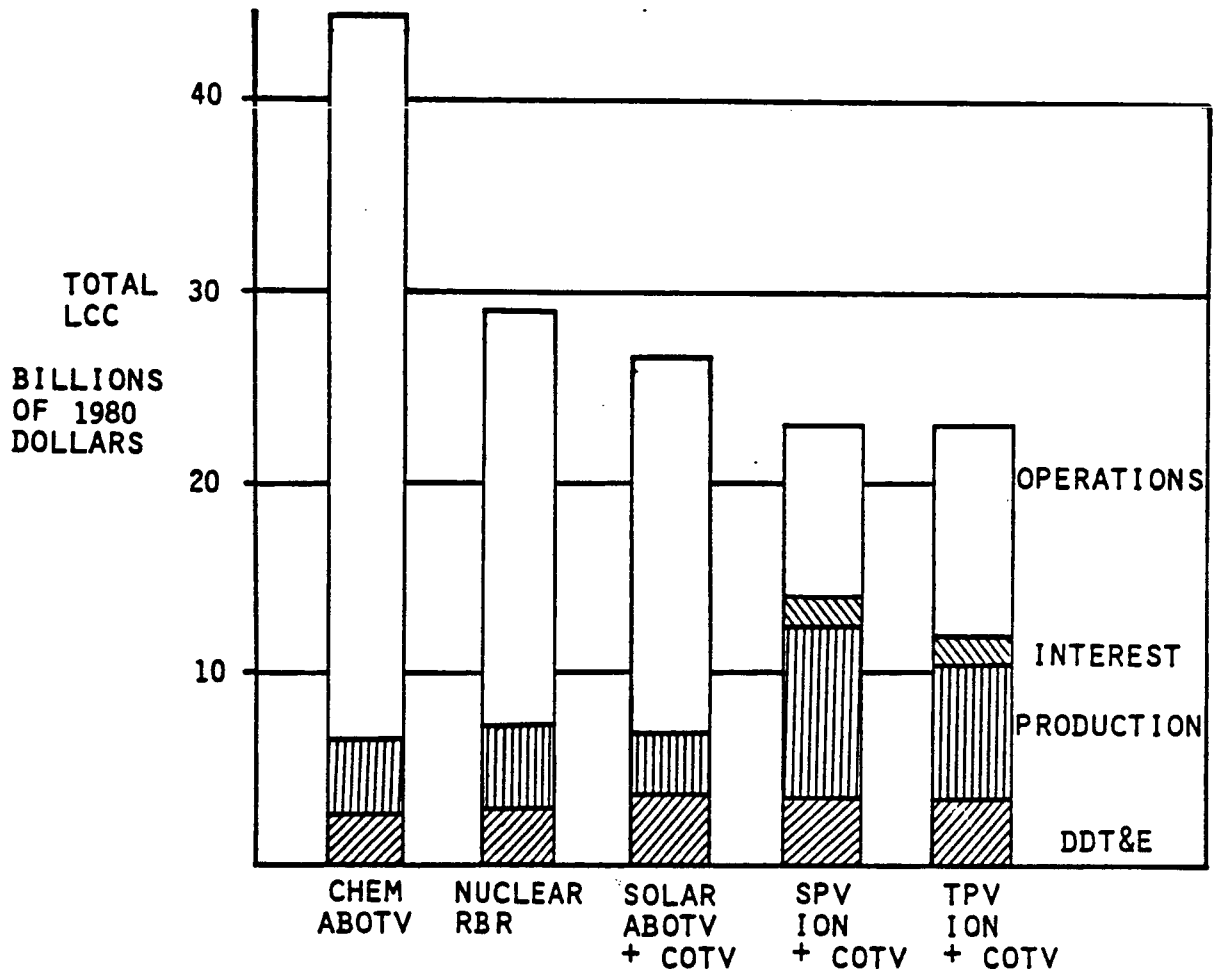
	SPACE-BASED CHEMICAL ABOTV	NUCLEAR ROTATING BED ROCKET	SOLAR THERMAL ABOTV +COTV	SPV ION +COTV	TPV ION +COTV
<b>OTV SYSTEMS</b>					
DDT & E	1035	1630	2005	1710	1635
PRODUCTION	1235	2890	1915	8570	6620
OPERATIONS	4860	4980	5160	4560	4560
	<u>7130</u>	<u>9500</u>	<u>9080</u>	<u>14840</u>	<u>12815</u>
<b>TANKER</b>					
DDT & E	215	310	410	350	350
PRODUCTION	275 (20)	260 (10)	240 (8+2)	85 (2+2)	100 (3+2)
OPERATIONS	495	315	295	205	220
	<u>985</u>	<u>885</u>	<u>945</u>	<u>640</u>	<u>670</u>
<b>SDV/RPS</b>					
DDT & E	1100	1100	1100	1100	1100
PRODUCTION	2250 (10)	1125 (5)	1125 (5)	450 (2)	450 (2)
OPERATIONS	33130	16465	14520	5545	7095
	<u>36,480</u>	<u>18,690</u>	<u>16,745</u>	<u>7095</u>	<u>8645</u>
<b>INTEREST DURING DELIVERY</b>	15	3.5	167	1242	1466
<b>TOTAL LCC</b>	<b>44610</b>	<b>29080</b>	<b>26940</b>	<b>23815</b>	<b>23495</b>

COSTS IN MILLIONS OF 1980 DOLLARS

## 3.2-10 Life Cycle Cost Summary by Hardware Element for High Model

	CHEM ABOTV	NUC RBR	SOLAR ABOTV +COTV	SPV ION +COTV	TPV ION +COTV
DDT & E	2350	3040	3515	3160	3085
PRODUCTION	3760	4275	3280	9106	7170
OPERATIONS	38,485	21,760	19,975	10,310	11,875
INTEREST	-	3.5	167	1242	1466
<b>TOTAL LCC</b>	<b>44,610</b>	<b>29,080</b>	<b>26,940</b>	<b>23,815</b>	<b>23,495</b>

## 3.2-11 High Model LCC by Category



3.2-12 Life Cycle Cost Summary Chart - High Mission Model

DDT&E and TFU costs for the high model are shown in Figures 3.2-1 through 3.2-5. The new large OTV's were assumed to be delivered in 2005, some 10 years after the smaller vehicles associated with the low model, and resulted in the avionics and propulsion DDT&E portions being costed at 10% of the values used for the low model. This savings was due to the assumption that the same technology would be used on the later high model vehicles as had been developed for the low model vehicles. OTV production quantities and system acquisition costs for the high model are summarized in Figures 3.2-6 and 3.2-7.

OTV operations costs for the high model were calculated using the same ground rules as before. The yearly costs are calculated in two periods: the first, 1995-2004, is identical with the low model; the second, 2005-2010, has extensive flight operations leading up to the first solar power satellite (SPS) and is costed separately (see Figure 3.2-8 for the operations costs breakdown).

Interest charges for the high model are shown in Figure 3.2-9. The interest was not charged for bulk cargo deliveries (e.g. nuclear waste disposal (NWD) and SPS demo) since they are not revenue-generating payloads.

LCC's for the high model are summarized in Figures 3.2-10 and 3.2-11. For the high model there appear to be significant differences in LCC's between propulsion concepts. This is because launch costs begin to predominate for this large mission model and the number of launches is largely a function of upper stage specific impulse. High model LCC's are shown in Figure 3.2-12. Observing the very large operations cost (mostly launch costs) of the chemical ABOTV, it appears that an investment in a heavy lift launch vehicle (HLLV) at the beginning of the high model would be a wise move. In this manner, an expenditure of \$5B to develop an HLLV by 2000 could save roughly half of the \$30B spent on fuel launches between 2000 and 2010. Development of an HLLV also appears to be cost effective for the nuclear rotating-bed rocket (RBR) and solar thermal ABOTV scenarios. Possible development of a new generation of launch vehicles was not part of this study and was not pursued any further. It does appear, however, that with the high model, we have reached the point where development of an HLLV is economically justifiable.